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High accuracy temperature measurement and monitoring of flow parameters using a multifunctional temperature probe

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An accurate and reliable temperature measurement is indispensable for the adjustment and efficient regulation of many technical processes. In some cases e.g. for optimizing efforts additional information about other process parameters like stream properties are essential. For this purpose normally the installation of additional sensors is necessary.

This publication describes the concept of a functionally integrated measuring instrument realised as a multifunctional temperature probe. This tool is capable to do temperature measurement in a highly accurate manner and a simultaneous determination of further process parameters. The high precise temperature measurement is accomplished by diverse temperature sensors inside one measuring instrument and an electronic circuit whereby the physically caused measurement deviation is corrected calculatedly. The geometric parameters of the sensor elements in combination with their respective signals allow the determination of certain stream properties. Further on a self-monitoring of the temperature probe is possible by using various combinations of thermocouples and resistance thermometers within this one instrument. Using this features the process reliability and efficiency can be increased while costs and efforts can be reduced.

To verify the functionality of the engineered measuring tools it is necessary to create a testing environment to elaborately examine the engineered prototypes. The precise test parameters were defined by tmg by taking the point of view of diverse customers into account and also respecting aspects of feasibility. The result is a setting of a turbulent pipe flow with a velocity between 1m/s and 30 m/s and a temperature range between room temperature and 200°C.

Based on this specifications concerning parameters and prototypes simulations about pipe flow and temperature profiles were carried out at the TU Ilmenau. Prototypes of the multifunctional temperature probe built by tmg are tested in the specifically developed test equipment.

The result of this project is a temperature probe which contains up to four temperature sensors and a mathematical model which is included in an electronic circuit. In addition to a high precise temperature measurement an independent self-control and the monitoring of divers process parameters is realised by one single measuring instrument. Thereby the presented project is able to make a significant contribution to the "industry 4.0". The paper will show the design of the multifunctional temperature probe and the developed test bench as well as first measurement results.

1 RESEARCH ISSUE

An accurate and reliable temperature measurement is indispensable for the adjustment and efficient regulation of many technical processes. Because of suboptimal conditions for temperature measurement concerning static as well as dynamic issues, safety corridors are implemented in technical systems. This causes intrinsically a buffer between desired and actual temperature, which leads to an unnecessary high energy consumption.

In some cases e.g. for optimizing efforts additional information about other process parameters, like stream properties, are essential for a flawless procedure management. Those parameters provide information about the overall state of the fluid, its composition and so on. For this purpose normally the installation of additional sensors is necessary.

2 OBJECTIVE TARGET

The intention of this task is a process monitoring which is improved in many kinds. The process reliability and energy efficiency are increased while cost and efforts concerning installation of further measuring points should be decreased.

This aim is realized through a functionally integrated measuring instrument embodied by a multi-functional temperature probe. The named temperature probe should provide a high precise temperature measuring and ongoing a simultaneously process monitoring. Additionally a function for self controlling of the probe is aspired.

2.1 Correction of the static-thermal measurement fault

With help of the intelligent networking of several temperature sensors a high precise temperature measurement which is almost independent on outer influences can be realized. Such a tool is really relevant in situations where a proper measurement installation isn't possible. A not proper installation occurs in gaseous fluids and/or when the ratio of installation length to diameter is less then 10.

With the help of two (or more) axial offset temperature sensors located in one protective tube one can draw conclusion about the heat transfer inside the temperature probe. By knowing these facts it is possible to retroactively correct the static-thermal measurement fault arithmetically. Using only two sensors for solving this problem you need to describe certain circumstances further more. For the application under various conditions a nonlinear approach, basing on the Fourier law concerning thermal conduction, is necessary.

2.2 Correction of the dynamic-thermal measurement fault

When the temperature of the fluid varies, a delayed response of the contact thermometer happens. Caused by the method of the indirect temperature measurement of contact thermometers a static faultless display is achieved where thermometer and fluid are arranged in thermal equilibrium.

This response delay can also be decreased with the help of several sensors inside one temperature probe. Depending on the design of the probe not every sensor inside shows the similar response delay. Regarding these differences concerning the diverse delays a forecast of the finally occurring temperature is possible before it is given.

2.3 Self monitoring

The result of installing multiple sensors inside one probe are redundancies concerning the measuring principle of the sensors. That means that thermocouples and simultaneously temperature measuring resistors can be implemented in various combinations. By reflecting of the diverse sensors among each other an inline error detection can be executed.

2.4 Fluid properties

Using multiple staggered temperature sensors the temperature field at the installation point of the thermometer is characterized. On the basis of the temperature distribution along the probe conclusions concerning properties of the fluid are possible. Herewith the controlling of technical processes beyond the temperature measurement is plausible. If those properties are familiar, sudden changes caused by aerodynamic stalls or leaks in pipe flows can be detected by this intelligent temperature probe.

3 PHYSICAL AND TECHNICAL BACKGROUND

3.1 High precise temperature measurement

The temperature measurement with the help of a contact thermometer is an indirect measuring method. This measuring method accordingly requires fluid and thermometer to be at the same temperature to display an accurate result in this case. That means that if operating fluid and temperature probe are standing in an adequate contact with each other temporally and physically, the temperature displayed by the thermometer equates the temperature of the fluid.

Practically this situation isn't always realizable. Due to special applications in many cases the thermometer is insufficiently integrated in the fluid. As a result and in a row with the heat transfer inside the temperature probe the temperature sensor shows a different temperature than the working fluid. That circumstance is so called the "static-thermal measurement fault caused by heat dissipation". Its quantity is directly depending on the temperature difference between working fluid and ambient temperature.

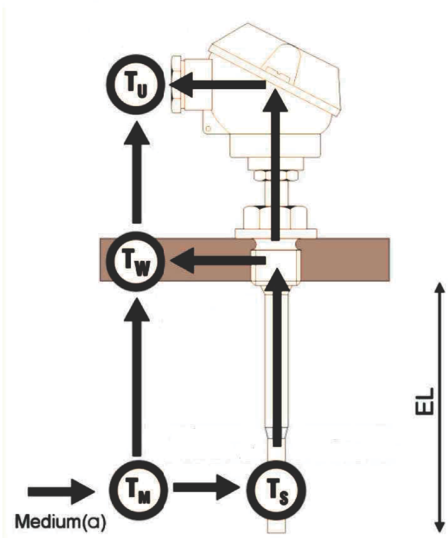

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Figure 3.1: Typical installation situation of a contact thermometer
T_U: ambient temperature
T_W: wall temperature
T_M: medium (fluid) temperature
T_S: sensor temperature

Figure 3.1 shows the typical installation situation of a contact thermometer. The black arrows illustrate the energy flow between diverse energy storage. The ratio between the installation length and the diameter of the thermometer as well as the kind of the process connection have a great influence on the static-thermal fault. To nearly eliminate fault mentioned above the ration should be executed in a way that the installation length is about minimum tenfold of the diameter. To realize this is one of the main problems in technical applications.

The solutions which were previously found to improve the static and / or dynamic performance of contact thermometers almost exclusive affect on constructional activities.

3.2 Monitoring of the fluid properties

The monitoring of the fluid properties doesn't happen directly via especially designated sensors but indirectly with the help of the temperature measurement. The name of the multi-functional temperature probe is derived from this fact. The precise advantage of this tool is to characterize several fluid properties only with help of one stem thermometer. The used connections between the different influencing variables are shown in figure 3.2

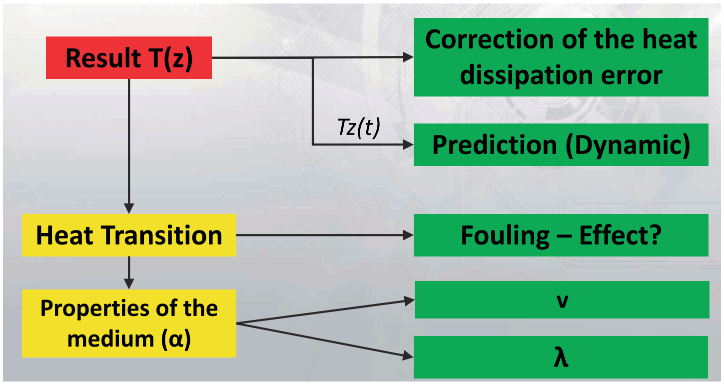


Figure 3.2: Chart regarding the determination of the fluid properties

The single temperature values indicate the temperature disposition inside the temperature probe. Accordingly, properties of the fluid like the heat transfer coefficient and derived from that the flow velocity or thermal conductivity of the fluid were concluded.

It has to be remarked that the characterization of certain fluid properties via this method only can be figured out if a few other properties are known. A detailed quantification due to this indirect manner is not possible. Therefore this characterization method is consequently useful for process monitoring or controlling but not for regulation tasks.

4 APPROACH

4.1 Experimental conditions

Applications scenarios

The precise test parameters were figured out by taking the point of view of diverse customers into account and also respecting aspects of feasibility.

The result is a setting of a turbulent pipe flow with a velocity between 1m/s and 30 m/s and a temperature range between room temperature and 200°C.

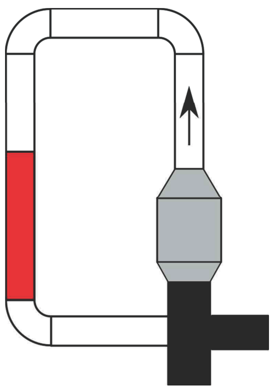
An essential item in this case was the substantial lower heat transfer coefficient in gaseous fluids on the contrary to liquid fluids. Because of this circumstance a correction of the thermal- measuring fault in gaseous fluids is much more advantageously.

The testing parameters result as following:

- temperature range: 25°C - 200°C
- flow velocity: $1\,{}^{m}/_{s}$ - $30\,{}^{m}/_{s}$
- temperature and flow velocity are adjustable separately

Test Bench

A test bench according to the specification named above was designed and realized by the IPMS of the TU Ilmenau. The test bench is, as shown in figure 4.1 carried out in “Göttinger Bauart” what means that test channel is executed as a closed loop. In consideration of the aimed temperatures of 200°C this fact is very reasonable regarding aspects of energy and controlling.



Abildung 1: Schematische Darstellung des Versuchsstands in Göttinger Bauart mit Radial-Lüfter (schwarz), Heizregister (grau) und Prüfstrecke (rot). Die Strömungsrichtung des Luftstroms ist eingezeichnet.

Figure 4.1: Schematic presentation of the test bench realized in “Göttinger Bauart”
With radial-fan (black), electric heating (grey) and measuring section (red).
The flow direction is illustrated.

The pipe of the test bench is designed in a modular way so that the measuring section is replaceable. The diameter of d=150mm of the measuring pipe takes the dimensions of the test subjects into account which have a diameter of d=6mm to d=12mm. The aim that the ratio between installation length to diameter of the temperature probe is minimum 10 for a nearly eliminated thermal measuring fault is reached when the test subjects are completely integrated in the measuring pipe.

An adaption of the diameter of the measuring pipe to other test objects or testing parameters is easily feasible in the future.

Figure 4.2: photo of the test bench

Figure 4.2 shows a photo of the test bench with its insulation (1), the automatic control (2), the electric heating (3) and the radial fan (4). Because of the temperature difference between the pipe flow and environment the complete pipe is insulated with mineral wool. That's why no additional cooling is necessary. The operating unit is a memory programmable control (SPS) with a graphic user interface. The functions of the test bench were controlled and monitored with it.

The adjustment of both command variables takes place manually. The flow velocity can be regulated directly via the frequency converter of the fan. The temperature in the measuring pipe is controlled with the help of two temperature measurement points - one in flow direction at the start and one at the end of the measuring pipe. By adjusting manually the electric heating depending on the current situation the flow temperature is tunable.

4.2 Test subjects

Figure 4.3 shows the basic scheme of a contact thermometer with up to 4 integrated temperature sensors.

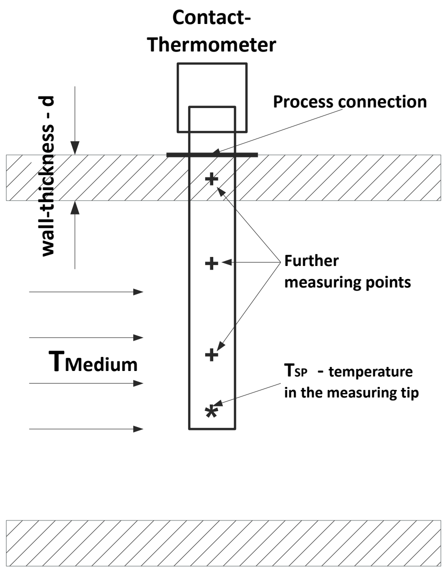


Figure 4.3: Diagrammatic plan with 4 axial offset sensors

To verify the temperature field inside the thermometer it is necessary to array the sensors in a way that enables to get a as much detailed picture of the temperature distribution as possible. The aim of this paper is now to find a prototype which completes these tasks.

Therefore two prior parameters of the basic construction of a cylindrical contact thermometer were varied:

- The diameter of the thermometer (measuring insert & protective pipe)
  - 4,5mm / 6mm / 9mm / 12mm
- The integrated sensors
  - thermocouple / measuring resistor
  - arrangement
    - axial offset
    - radial position

The produced samples so far including their primary use are listed in table 4.1

Table 4.1: Overview concerning the sensor placement in the temperature probe

sensors			application
count	kind	**positioning**	
2	1x Pt100, 1x TC	axial offset	basic correction of the static measuring fault reducing of the dynamic measuring fault
4	4x TC	axial & radial offset	independent precise correction of the static measuring fault, research concerning fluid dynamic effects
4	4xPt100	axial & radial offset	independent precise correction of the static measuring fault, comparison of TC and RTD in this special case

The proof of concept concerning the correction of the static and dynamic measuring fault is evidenced with the help of the initial sample which is only equipped with two temperature sensors. On the basis of the therefrom determined results, samples with diverse differently arranged sensors have already been build, and will be in future.

The stages of development of the single sample constructions is as following:

1. Initial sample with two sensors - 1x RTD + 1x TC
2. Measuring insert made of sheathed cable with four thermocouples
3. Measuring insert with four Pt100 measuring resistors
   - The diameters are equal at first with d= 6mm
4. On this basis further designs will be created

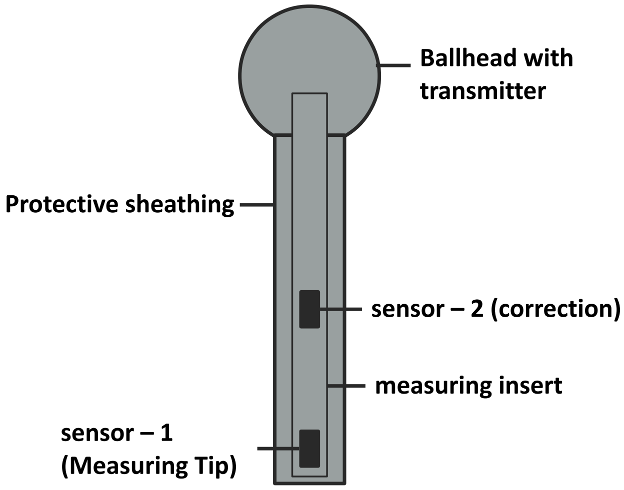


Figure 4.4: schematic presentation of a contact thermometer with 2 offset sensors

The initial sample which is a narrowed variation with only two sensors, shown in figure 4.4, typifies the starting point of the researches. In this version a platinum resistance sensor class AA and a thermocouple TypT class1 have been applied. Herewith a linear correction of the static thermal measuring fault is possible. Therefore a calibration with an additional correction factor is necessary. The complex concept with the aid of the Fourier law concerning heat conduction isn't possible yet because of the insufficient number of input values.

Furthermore an estimation of the heat transfer conditions of the fluid is feasible by regarding the the relation of both temperature values.

The next step is a thermometer with four sensors embodied by a fourfold thermocouple. The four thermoelectric measuring tips are made of a double sheathed cable. This kind of design has two significant advantages. Firstly the diameter of the measuring insert can be very slim in reference to the number of measuring points. It is possible to achieve a diameter of only 3mm whereas for a measuring insert with 4 measuring resistors at least a diameter of 6mm is needed.

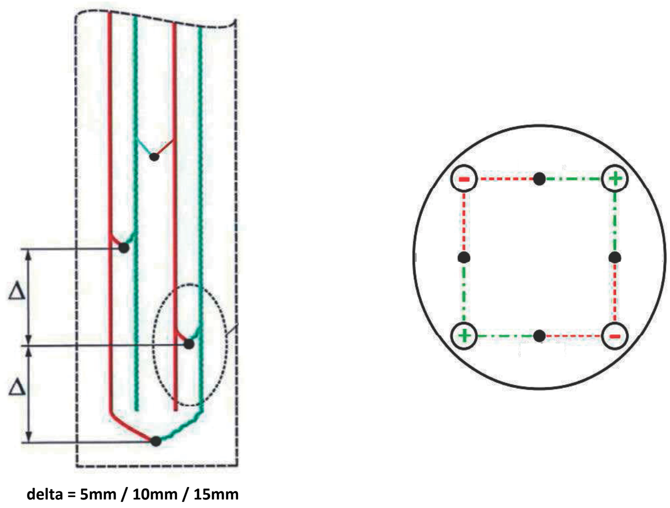


Figure 4.5: Fourfold thermocouple made of a double sheathed cable

When using the configuration shown in figure 4.5 it is furthermore evident to perform a flow-selective measurement.

Because of the arrangement of the thermoelectric leads inside the sheathed cable the four measuring tips aren't located in the middle of the circular area of the thermometer but in an eccentric formation. Thereby an adjustment of the orientation of the measuring insert depending on the measuring task is feasible.

5 FIRST RESULTS

The initial sample shown in figure 4.4 was tested in the test bench realized by the IPMS. The results are shown in figure 5.1

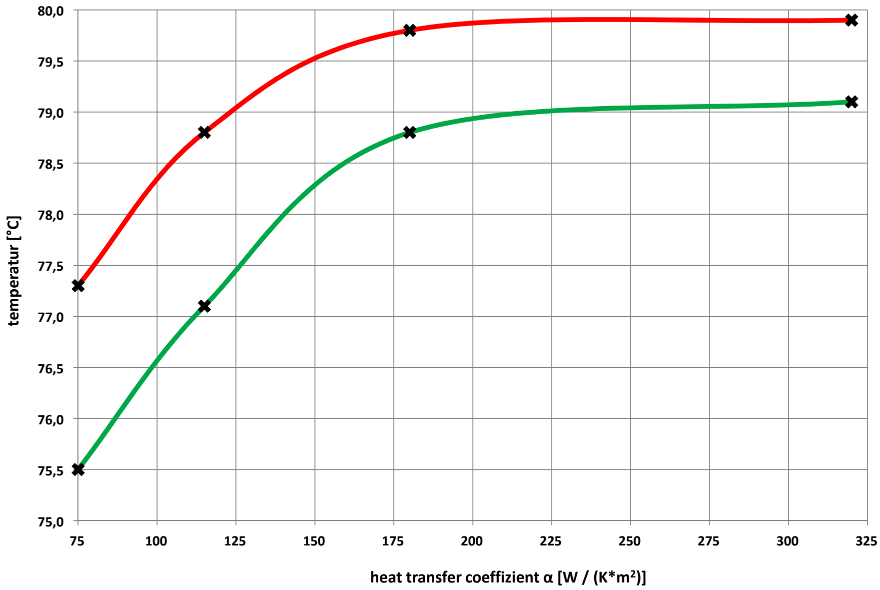


Figure 5.1: temperature measuring depending on the heat transfer coefficient
red: Pt100 - temperature sensor located in the measuring tip
green: Thermocouple TypeT 10mm axial offset

Looking at this diagram two fact are already obvious:

For one thing it is clearly visible that the difference between the two sensor is almost steady about 2K while the thermal measuring fault decreases with a increasing heat transfer coefficient α. This constant relation can be easily used for algorithm to correct the static thermal measuring fault. This solution is only valid for similar conditions concerning the application and the design of the thermometer. Because of the only two input values which are processed necessarily a linearization at this special operating point is done.

Secondly you can see that if the heat transfer coefficient is more than 200 $^{W}/_{m^2 \cdot K}$ the thermal measuring fault of the primary sensor is nearly zero. That's why a correction in this range is obsolete.

6 OUTLOOK

At present first samples are designed and produced while the test bench at the IPMS is gradually putted into operation. The first results which were mentioned above will be completed and extended while, based on the gained results, further parameters of the test object will be varied.

The finally Intention is a precise and reliable correction of the thermal measuring faults.

Additionally the monitoring of several process parameters is aspired insofar there is information about further conditions.

the self monitoring of the system is practicable by using sensors with different measuring methods like RTDs and TCs.

7 References

[1] F. Bernhard (Hrsg.): Handbuch der Technischen Temperaturmessung, Springer-Verlag 2014

8 Contacts

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